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A Digital Positioning System of the Slewing and Inching Type

by

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Research Establishment Risö
Electronics Department

Abstract

This report describes a logic scheme which forms the basis for the design of a positioning system for digital control of mechanical motions. In order to ensure a desired position denoted reference R, the system is so arranged that the mechanical parameter always approaches R from an off-set reference R- δ R with a suitable low speed. This provides the possibility of avoiding the effect of a dead zone in the mechanical transmission, and the stored mechanical energy may be released during the low-speed motion.

Table of Contents

Introduction

A great deal of the experimental equipment around the reactors at Risö is provided with positioning channels for the setting of experimental parameters such as spectrometer axis, absorbers, samples, etc. Special considerations in designing the system described make it possible by simple procedures to alter measuring ranges and the number of positioning channels.

General Description

In the block diagram fig. 1 the principle of the digital positioning system is shown. The desired position of the output axis may be set in the shift register shown to the left. This information is represented by a number of binary-coded decimal decades. The digital-to-analogue converter and the subtractor, which serve the purpose of giving the error signal with sign, are shown in the following two blocks. The output is one of the three possible signals; the position is $\gtreqless$ the reference. These signals are handled in a unit denoted ERROR VALUE LOGIC, which decides, on the basis of the reference demanded and the instantaneous position, which motion pattern is to be followed to obtain a reproducible desired position. In the practical layout, stepping motors are used because they may be run at a very low frequency when approaching the reference (inching mode); in addition the motors brake rapidly because of the permanent magnetization of the rotor. The pattern generator shown in the figure has inputs for inching mode, slewing mode and direction. It operates in connection with the motor selector, which, on a command from the address decoder, switches on a motor in a chosen positioning channel. The position decoder shown in the feedback loop converts the reflected decimal code from the shaft digitizer either to decimal form or to binary-coded decimal for connection of various types of read-out or displaying equipment. A more detailed description of the individual components and units making up the system is given below.

Shaft Digitizer

The basic part of this mechanical converter is a circular disc covered with a number of concentric tracks, each consisting of conducting alternating with non-conducting segments. All conducting segments are in electrical connection with each other and with a pick-off brush for the common current. All the individual tracks are supplied with pick-off brushes from which the entire position information may be derived. The shaft digitizers used in the system described are coded in a reflected decimal code. Three decades are placed on the surface of the disc so that during one revolution of the input shaft one thousand combinations are formed sequentially on the output terminals. The code used within the individual decades is a variant of the Gray code (cyclic permuting binary). An essential characteristic of this unit step code is that only one bit changes in any position; thus ambiguities in read-out are avoided. In fig. 2 is shown a section of the coded pattern, the decoding circuit for which will be dealt with in the next section. The single-turn shaft digitizer described forms the basic element in a building block system in which the measuring range may be extended by adding a desired number of decade drums mechanically cascaded with the gear reduction 1:10. These drums are provided with the same coded pattern as the disc, but each covers one decade. On account of the unavoidable mechanical dead zone between the drums, the added decades must be read out by means of double pick-off brushes in connection with a selecting circuit (anti-ambiguity logic) as described below. The capacity of the shaft digitizer is thus dependent on the number of decade drums added, while the resolution is determined by the three decades on the disc.

Decoder

In fig. 3 the fundamental design of the four-decade decoder is shown. The shaft digitizer used is a Hilger and Watts FD8/FD15 unit[2)] in which the FD8 covers three decades on a coded disc, as described above, and the drum FD15 makes up the fourth decade. The individual decoders corresponding to the decades $x10^0$, $x10^1$, $x10^2$, and $x10^3$ are composed of a number of complementary circuits. Fig. 4 shows a block diagram comprising a single decade including the built-in logic specified above.

As it appears from fig. 2, repeated decades form a reflected pair. This pattern continues throughout the decades and makes it possible by introducing odd-parity circuits to separate odd and even decades before decoding takes place. Connection of the decoders $x10^0$, $x10^1$ and $x10^2$ belonging to the FD8 is consequently performed by an EXCLUSIVE OR logic, denoted EO in fig. 3, in such a way that an EO circuit belonging to a certain decade may be controlled by odd digits in the next higher decade. The logic is expressed in the Boole notation in fig. 5. The two EO circuits acting in the decoders $x10^2$ and $x10^3$ serve the purpose of reversing the counting direction conveniently. As mentioned earlier, the outputs from the drum digitizer must pass through an antiambiguity logic before decoding.

The pick-off brushes referred to as "Lead" and "Lag" in fig. 3 are so spaced that at the 999/000 transition of the fine scale on the disc they are 1/4 digit on either side of any transition on the coarse scale on the drum. The principle of the antiambiguity logic is shown in fig. 6. Basically it is an electronic switch selecting alternately the leading and the lagging brushes, and controlled, as seen in fig. 3, from the preceding, lower decade ($x10^2$) in such a way that the leading brushes are selected as the decade is reading from 0-4 and the lagging brushes when the decade is reading from 5-9, with the input axis turning in a clockwise direction. From the point of view of decoder output it means that all 9/0 transitions are simultaneous and that a certain amount of dead zone in the gear train between the added decade drums may be tolerated.

Subtractor

Basically this unit is designed as a series comparator, the comparison being performed in the individual decades by sequentially weighting the current, which may be picked off from the digital-to-analogue converters on the reference and position sides. In fig. 7 the reference side is on top and the position side at bottom. Further the figure shows the comparators denoted C_0-C_3, the input of which forms the summing junctions for the currents picked off from the two information sides. The comparators are ternary threshold circuits, giving information to the succeeding decision logic on whether the input current is positive, zero or negative, corresponding to whether the reference is $\gtreqless$ the position in the individual decade. Outputs for the entire information from all decades are shown to the right. After read-in of the reference the comparators must decide whether $P \gtrless R$ ($P = R$ is ignored as irrelevant in this connection). The problem may be reduced to the decision as to which of the two binary digits P and R is the larger. This will be determined by the most significant bit (i. e. the most significant decade) where p and r are different and the relevant comparator responds to one of its outputs $p \gtrless r$.

Fig. 8 shows this in a little more detail. The D/A converter is composed of binary-weighted resistors on the reference and position sides. The transistors V1-V8 act as ideal switches since they are a type with a low leak current in the off-state and a small spread in the voltage across the transistor in the on-state. The sign of the difference current is determined by the comparator, whose active elements are the emitter-coupled, complementary pair V9 and V10. With P1 and P2, the bias adjustment necessary to obtain the ternary characteristic of the comparator is performed. In the table is shown the mode of operation of the terminating decision logic, which is supplied with gates for series and parallel comparison, named SC and PC respectively. The interconnection of the individual decade comparators appears from fig. 7. It is seen that all individual outputs $p_i < r_i$ and $p_i > r_i$ are joined in OR-gates, while the outputs $p_i = r_i$ connect one comparator with the gate SC_{i-1} at the next lower comparator. Consequently, none of the comparators C_i is able to give any information on whether $p_i \gtreqless r_i$ until the more significant comparator has indicated that $p_{i+1} = r_{i+1}$. Before referring to the application of the comparator as a parallel subtractor, it is convenient to look at the kinematics in the positioning system.

Motion Patterns

As the programming of a position must be performed independently of the preceeding position, some characteristic conditions may occur which make it desirable to introduce an error value logic giving a reproducible desired position. Let δR indicate a small pre-selected displacement of the read-in reference which takes into consideration the dead zone in the mechanical transmission. One of three characteristic starting positions may occur which forms the basis of a certain motion pattern.

(a) $P < R - \delta R < R$

Fig. 9a shows a starting position $P < R - \delta R$. Slewing motion is to take place with increasing angular values until the off-set reference $R - \delta R$ is reached; the motion is then slowed down to a suitable low speed(inching mode), over the last distance δR.

(b) $P > R > R - \delta R$

In fig. 9b the starting position is greater than the reference. Slewing motion is to take place with decreasing angular values, passing the cancelled reference R and stopping at $R - \delta R$. After reversal of the direction and transition to the inching mode, the motor stops at $P = R$.

(c) $R > P > R - \delta R$

In this angular section, inching mode motion takes place until $P = R$.

Generation of R - δ R

The span of δ R is optional over one or more decades. In the prototype (fig. 7) it has been sufficient to let δ R act in the least significant decade. Actually it is a resistor which is to be switched in the summing junction at the decade comparator in accordance with the decision of the error value logic. Generation of the off-set reference R - δ R is initiated by disconnection of the entire information P, which is momentarily replaced by δ R. As any of the digits in the reference R is represented by a number of discrete current steps $n_r \cdot i_K$, where i_K is the quantizing unity, the quantities to be momentarily compared are

$$R = \sum_{j=0}^{3} n_{rj} \cdot i_K \cdot 10^j; \quad n_{rj} = 0, 1, 2 --- 9, \text{ and}$$

$$\delta R = n_{\delta o} \cdot i_K . \quad n_{\delta o} = 1, 2 --- 9 .$$

δ R also appears as a number of discrete current steps, but acting only in the least significant decade. As n_{ro} and $n_{\delta o}$ may independently accept arbitrary integers, the difference $(n_{ro} - n_{\delta o}) \cdot i_K$ can appear with either positive or negative sign. If negative, it will be necessary to borrow from the next higher decade, in other words to subtract the quantizing current i_K from the summing node on the comparator C_1 and adding 10 i_K to the corresponding node on C_o. This process is performed by opening the above-mentioned gates PC_o, PC_1 and PC_2 for a brief moment (fig. 7). According to the sign of the input current to the comparators, the corresponding outputs may turn on the latches LP_o, LP_1 or LP_2, thus connecting the borrowed currents. This connection will only be made if $p > r$ in the decade concerned and is extended to the highest decade because in certain cases it is necessary to know the entire quantity R. After the generation of R - δ R the parallel comparison is turned off and the position information P restored, after which running series comparison may be realized.

Error Value Logic

This unit establishes and remembers the characteristic angular sections while passing them during a setting process and on the basis of this decides the motion pattern to be followed. To the right in the logic diagram are shown the outputs to the voltage pattern generator. To the left are the outputs for connection of the off-set reference δ R to the summing junction on C_o and in addition a control output for resetting of all LP with subsequent cancelling of the borrowed currents i_K and 10 i_K on the transition from slewing to inching mode. Cancelling of δ R must be realized either for P = R - δ R or in the following situation: In the state of R> P> R - δR (fig. 9c) the error value logic first of all establishes that P< R by setting L_1, consequently generating R - δ R by setting LδR. This means that now P> R - δR, and L_3 goes into the set position. Finally, L_1 and L_3 turn on L_2 jointly, the latter resetting and blocking LδR, thus starting the stepping motor in the inching mode until P = R.

The control circuit shown in fig. 11 is to carry out the following programme on external command (set axis):

(1) Series comparison for establishing whether the starting condition is P = R.
Command signal from the error value logic starts the following process:

(2a) if P = R: axis settled,

(2b) if P $\neq$ R: disconnection of series comparison and position information P, parallel comparison between R and δ R for generating R - δ R,

(3) restoring of P followed by running series comparison between P and R - δR.

The connection in the procedure described is illustrated in the flow chart, fig. 12. The time dependence between the individual functions is shown in the time chart, fig. 13.

Driving System

For the positioning system a step motor of the commutated DC type (SLO-SYN SS250) was chosen. It is a twin-phase synchronous motor supplied with a permanent magnetic rotor forming a unidirectional flux in the air gap between rotor and stator. With the voltage pattern indicated in fig. 14 supplied to the phases X and Y, the motor will advance 200 steps per revolution. Each step is 1.8^o and specified with an accuracy of $\pm$ 0.09^o. The DC-flux builds up a holding torque opposing any rotational force applied externally to the shaft. This torque may be increased by superimposing a DC voltage on the phases, which is utilized in the pattern generator described below (fig. 15). It is composed of two bistable multivibrators MV1 and MV2. The output from MV2 controls the firing gate to the SCR in one motor phase and, in addition, sets up the DC conditions for the logic which operates the SCR in the other phase. The correct timing of the logic output is obtained from MV1 (signal $\bar{A}$) while terminal A is the signal for sampling of the direction command. DC commutated running of the motor offers the advantage that the four steps making up a period may be separately controlled, which makes it possible to inject a single step corresponding to 1.8° on the output axis. The individual steps represent stable positions separately. At a suitable low commutating frequency, the motor will come to rest between consecutive transitions, momentarily locked by the magnetic DC-flux and the superimposed phase current. A more detailed description of the design is given in reference 3. The derivation of the transfer function for unit step dynamics given in brief below reveals some interesting similarities between the stepping motor during a single step and more conventional position servos. On the application of a voltage E at one of the phases of the motor in accordance with the voltage pattern shown in fig. 14, the current

$$J(s) = \frac{E(s) - K_e \cdot s \cdot \theta(s)}{R} \tag{1}$$

will arise.

In linearized approximation this will cause the torque

$$T = K_t \cdot J(s) . \tag{2}$$

$$T_r = K_r \cdot \theta(s) \tag{3}$$

represents the restoring torque arising from the detent characteristic of the step motor.

For a small deviation of the rotor from the stable position it may be assumed linear.

The net torque accelerating the motor is

$$T - T_f - T_r = K_t \cdot J(s) - K_f \cdot s \cdot \theta(s) - K_r \cdot \theta(s) = J \cdot s^2 \cdot \theta(s) . \tag{4}$$

The notation used throughout is as follows:

E(s), Laplace transform of applied voltage, volts

J(s), Laplace transform of current in winding, amperes

θ(s), Laplace transform of angular position of rotor, radians

R, Resistance of winding, ohms

K_e, Voltage constant of motor, volts/rads/seconds

K_t, Torque constant, Nm/amperes

K_r, Restoring torque constant, Nm/rads

K_f, Equivalent viscous friction, Nm/rads/seconds

J, Total moment of inertia referred to the motor shaft, $kg \cdot m^2$.

Substituting (1) in (4) and solving for the transfer function, we have

$$\frac{\theta(s)}{E(s)} = \frac{\frac{K_t}{J\,R}}{s^2 + \frac{K_f + \frac{K_t \cdot K_e}{R}}{J}\, s + \frac{K_r}{J}} \quad . \tag{5}$$

This equation shows that in the region of a single step the motor may be regarded as a second-order system with the natural frequency

$$\omega_n = \sqrt{\frac{K_r}{J}} \tag{6}$$

and the damping ratio

$$\zeta = \frac{1}{2}\; \frac{K_f + \frac{K_t \cdot K_e}{R}}{\sqrt{J \cdot K_r}} \quad . \tag{7}$$

The block diagram of the motor is shown in fig. 16. Application of a step voltage to one of the windings $E(s) = \frac{E_o}{s}$ corresponding to a step angle $\theta(s) = \frac{\theta_o}{s}$ yields the response of the output shaft

$$\theta(s) = \frac{\theta_o}{s}\; \frac{\omega_n^2}{s^2 + 2\;\zeta\omega_n\, s + \omega_n^2} \quad . \tag{8}$$

Converting this equation to the time domain, we have for $\zeta < 1$

$$\theta(t) = \theta_o(1 - e^{-\zeta\omega_n t}(\cos \omega_n \sqrt{1-\zeta^2}\, t + \frac{\zeta}{\sqrt{1-\zeta^2}}\, \sin \omega_n \sqrt{1-\zeta^2} t)). \tag{9}$$

Application of the voltage pattern shown in fig. 14 yields at the output shaft a staircase curve with transients given by equation (9).

In the prototype used, the damping ratio was somewhat smaller than one. This gives an overshoot with a peak value of

$$M_p = e^{-\frac{\zeta}{\sqrt{1-\zeta^2}}\pi} ,$$

which establishes the kinematic condition in the gearing transmission between the step motor and the shaft digitizer that at least two stable states must occur in the motor for one bit change in the digitizer. It is usually necessary to choose a higher number of stable states, depending on the scattering of the bits around the average value.

Conclusion

In order to test the equipment in all discrete positions of the shaft digitizer and for all electronic functions, a punched-tape programme has been produced on the GIER computer of Risö. By this test it was found, as described above, that the bits which define the angular positions of the shaft digitizer sometimes showed too much scattering, resulting in an unstable system for certain positions. A method of testing transition scattering in shaft digitizers is given in ref. 6.

The motor type used in the positioning system is well suited for applications where high speed is not the dominating factor. Further, this closed loop component seems to be advantageous compared with the linear positioning system involving servo amplifier, stabilizing tachometer and reduction gear train. These evaluations together with a more detailed description are given in refs. 4 and 5.

Acknowledgements

The author wishes to express his thanks to J. Rasmussen and K. B Hansen for valuable comments and advice during the development of the system described. He also wants to thank T. Hviid and Sv. Nielsen for valuable assistance.

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4) F. Nishida, S. Mizuno and I. Fujisawa, Dynamic Performance of Stepping Motor. Electrical Engineering in Japan. 84, No. 9, 22-30 (1964).

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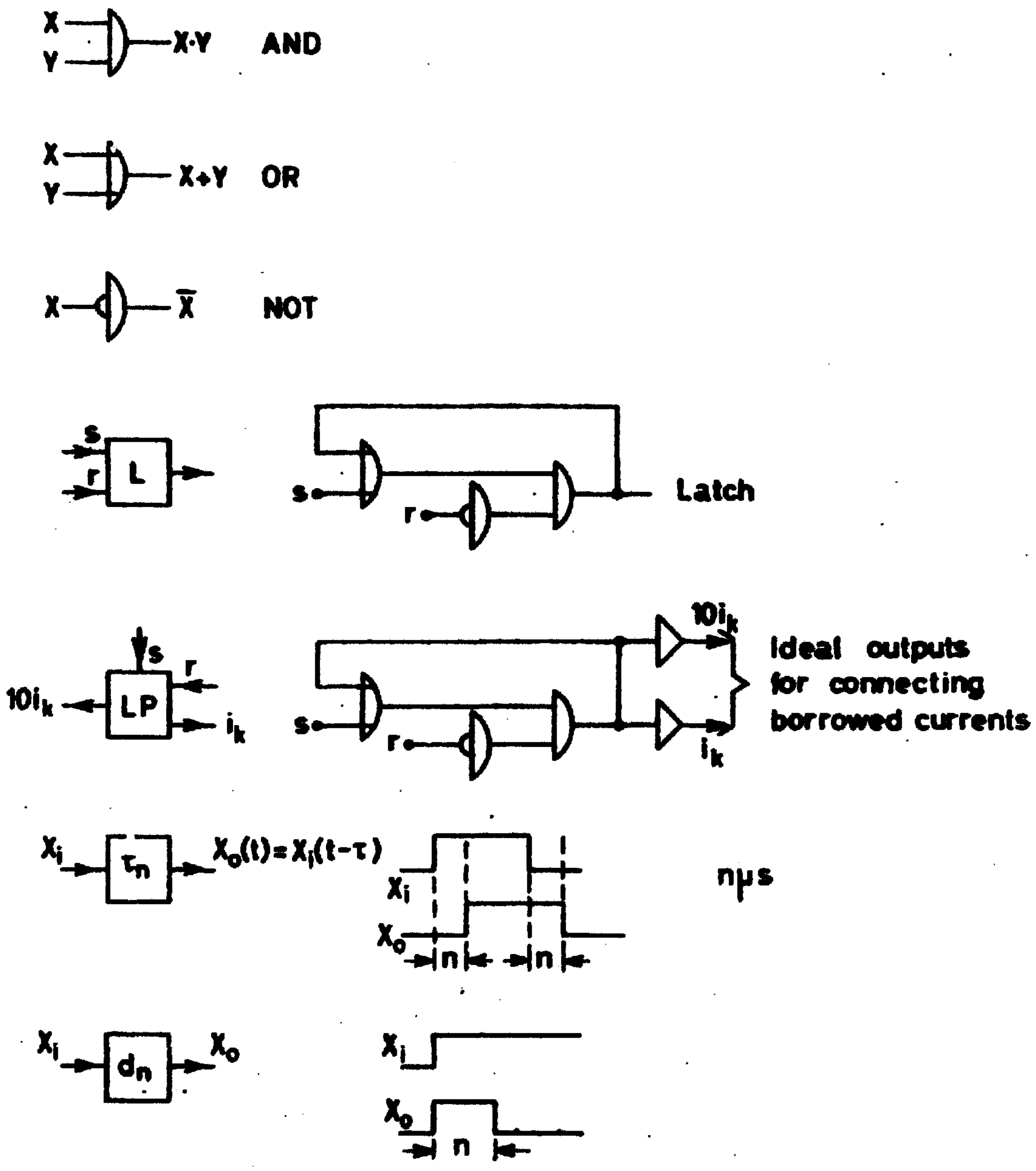
Pt. 1: Stepping vs. Stepless Control. 7, No. 11, 123-127 (1960).
Pt. 2: Operation and Analysis. 7, No. 12, 97-107 (1960).
Pt. 3: Applications. 8, No. 1, 85-88 (1961).
Pt. 4: Today's Hardware. 8, No. 3, 133-135 (1961).

6) K. E. Neisig, Testing Transition Scattering in Shaft Digitizers. Electronics Letters 2, No. 6, 222 (1966).

LOGIC SYMBOLS and ABBREVIATIONS



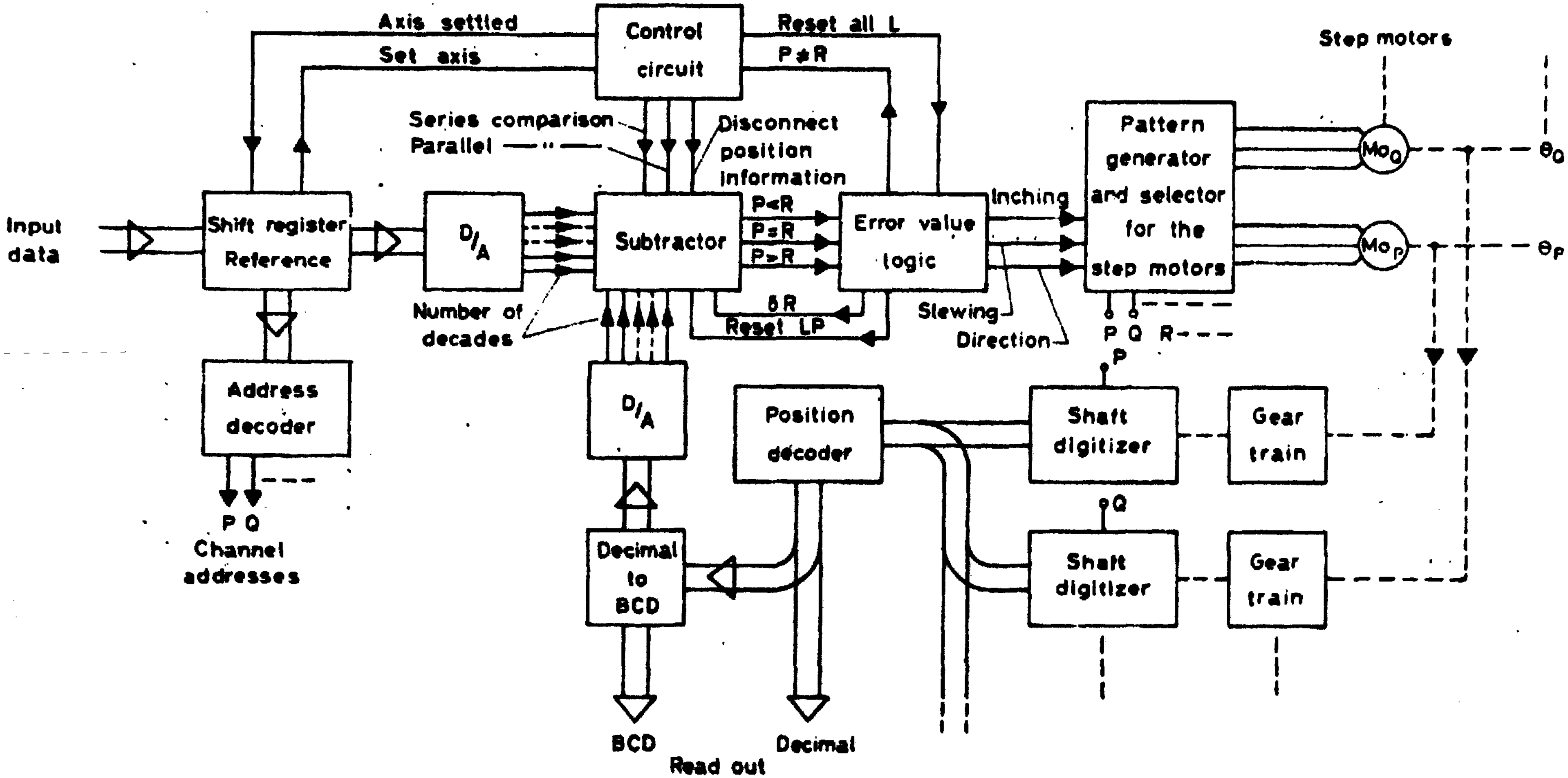


Fig. 1. BLOCK DIAGRAM OF POSITIONING SYSTEM

Decimal digits		Reflected decimal digits		Decade parity
0 0 0		0 0 0		
0 0 1		0 0 1		
0 0 2		0 0 2		
0 0 3		0 0 3		
0 0 4		0 0 4		
0 0 5		0 0 5		even
0 0 6		0 0 6		
0 0 7		0 0 7		
0 0 8		0 0 8		
0 0 9	shift	0 0 9	keep	
0 1 0		0 1 9		
0 1 1		0 1 8		
0 1 2		0 1 7		
0 1 3		0 1 6		
0 1 4		0 1 5		
0 1 5		0 1 4		odd
0 1 6		0 1 3		
0 1 7		0 1 2		
0 1 8		0 1 1		
0 1 9	shift	0 1 0	keep	
0 2 0		0 2 0		
0 2 1		0 2 1		
0 2 2		0 2 2		
⋮ ⋮ ⋮		⋮ ⋮ ⋮		even

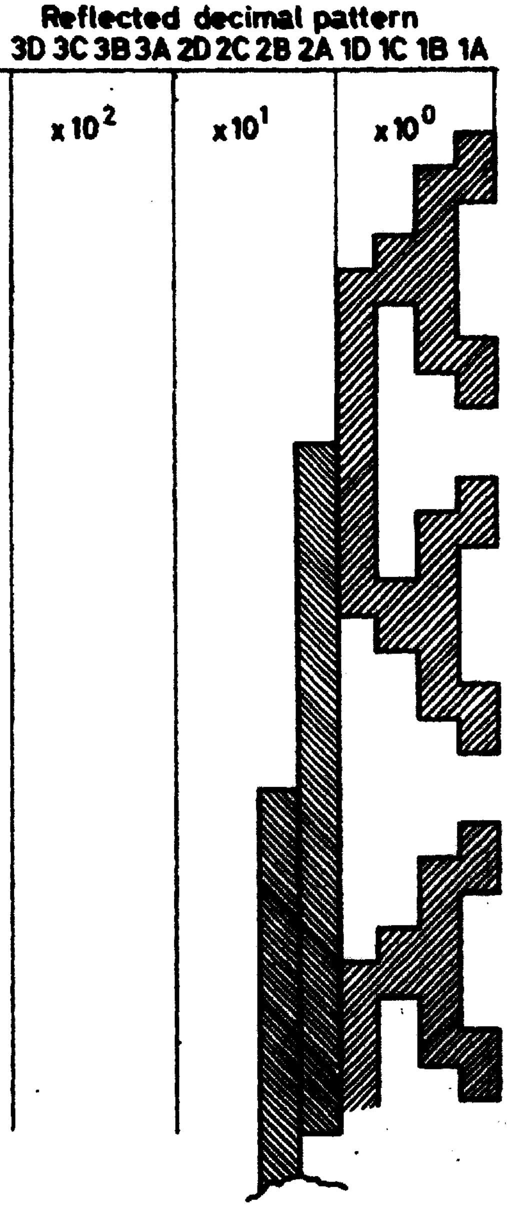


Fig. 2. SECTION OF REFLECTED DECIMAL CODE

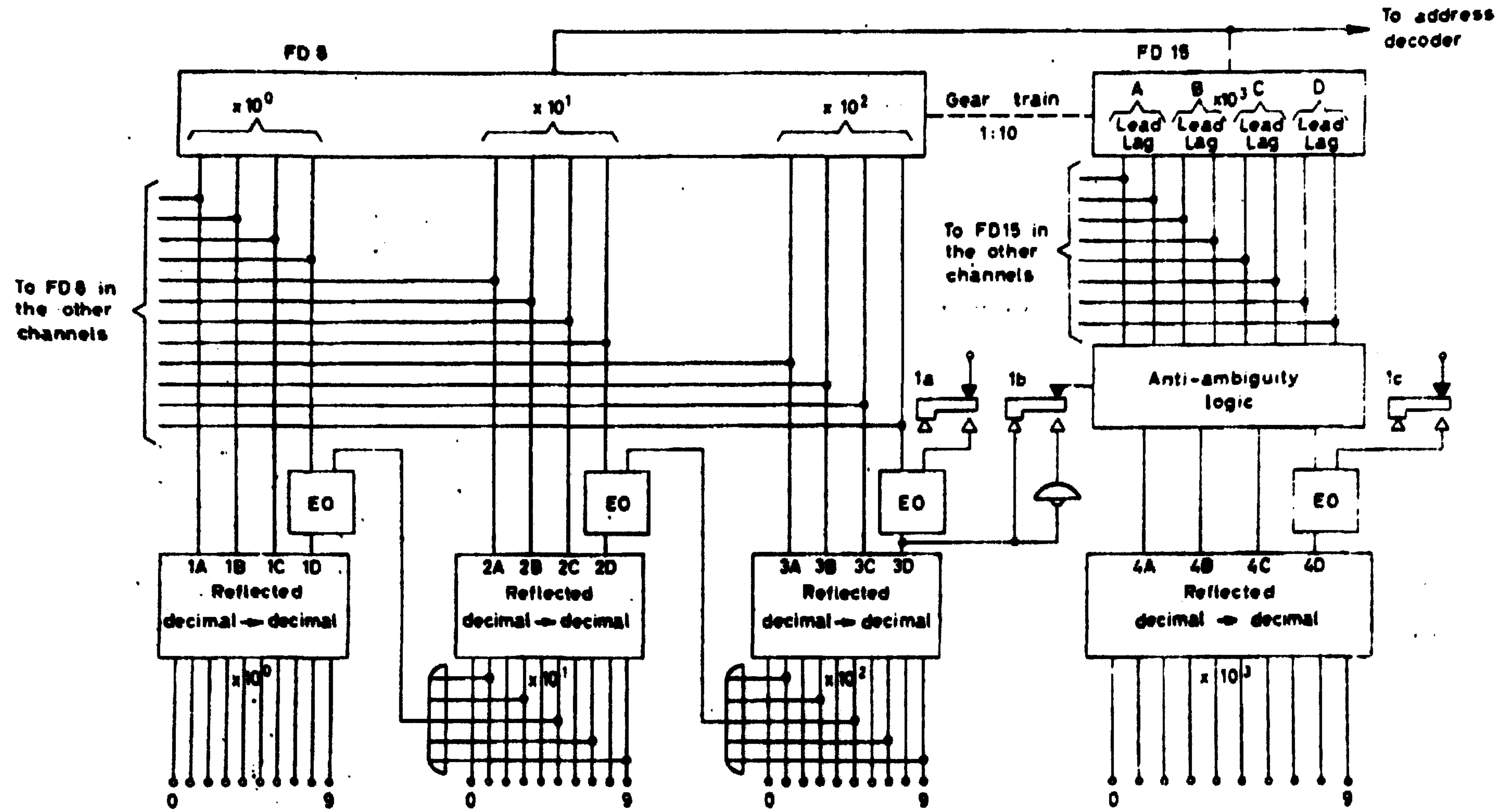
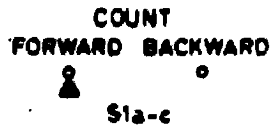


Fig.3. SHAFT DIGITIZER FD8/FD15 AND DECODING UNIT



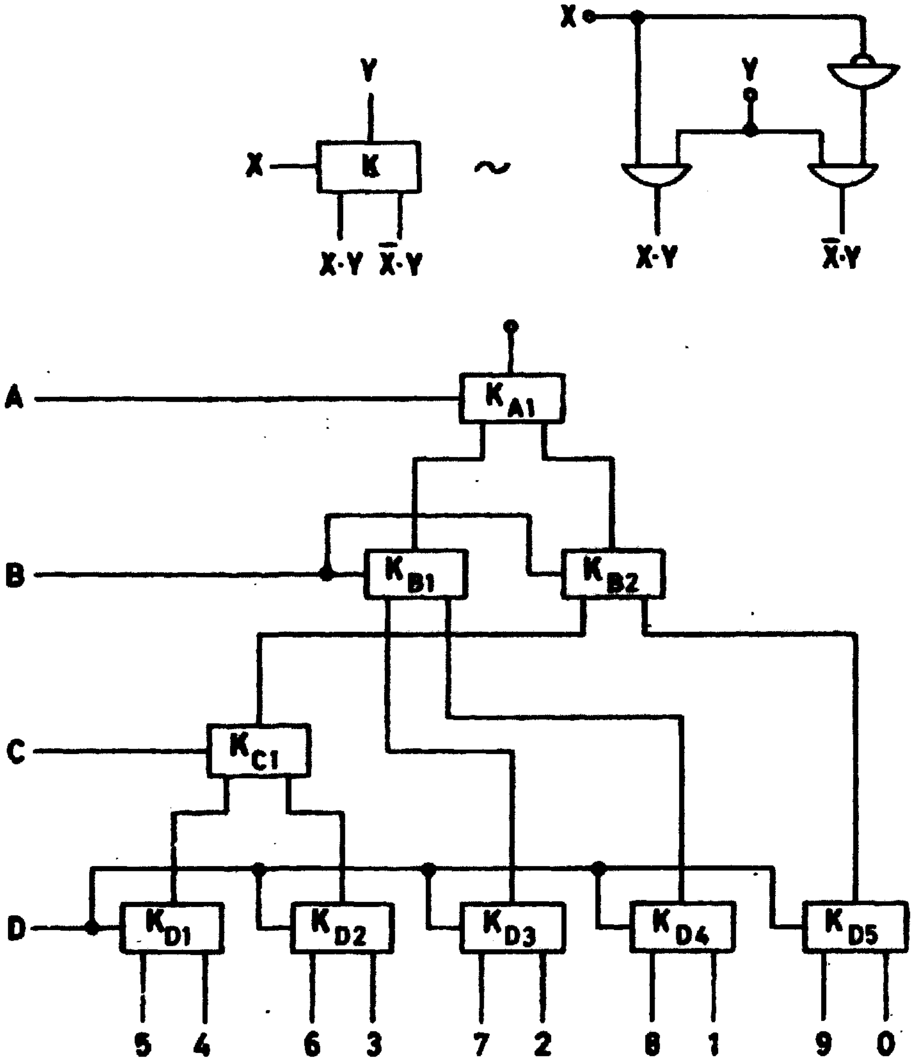


Fig. 4. REFLECTED DECIMAL TO DECIMAL

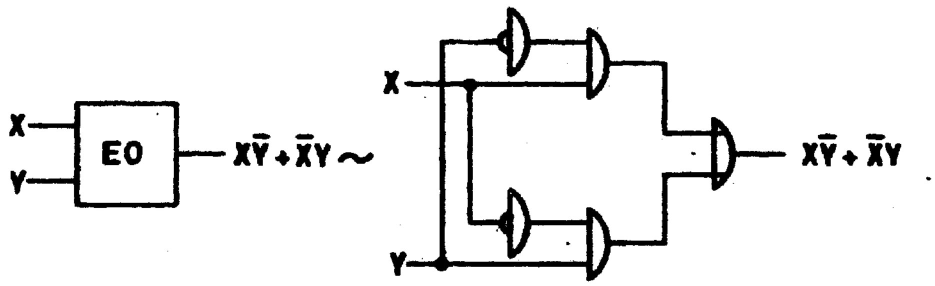


Fig. 5. EXCLUSIVE OR

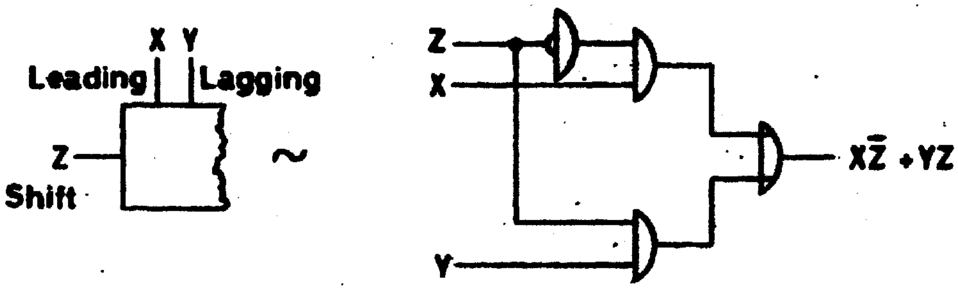


Fig.6. ANTI-AMBIGUITY LOGIC

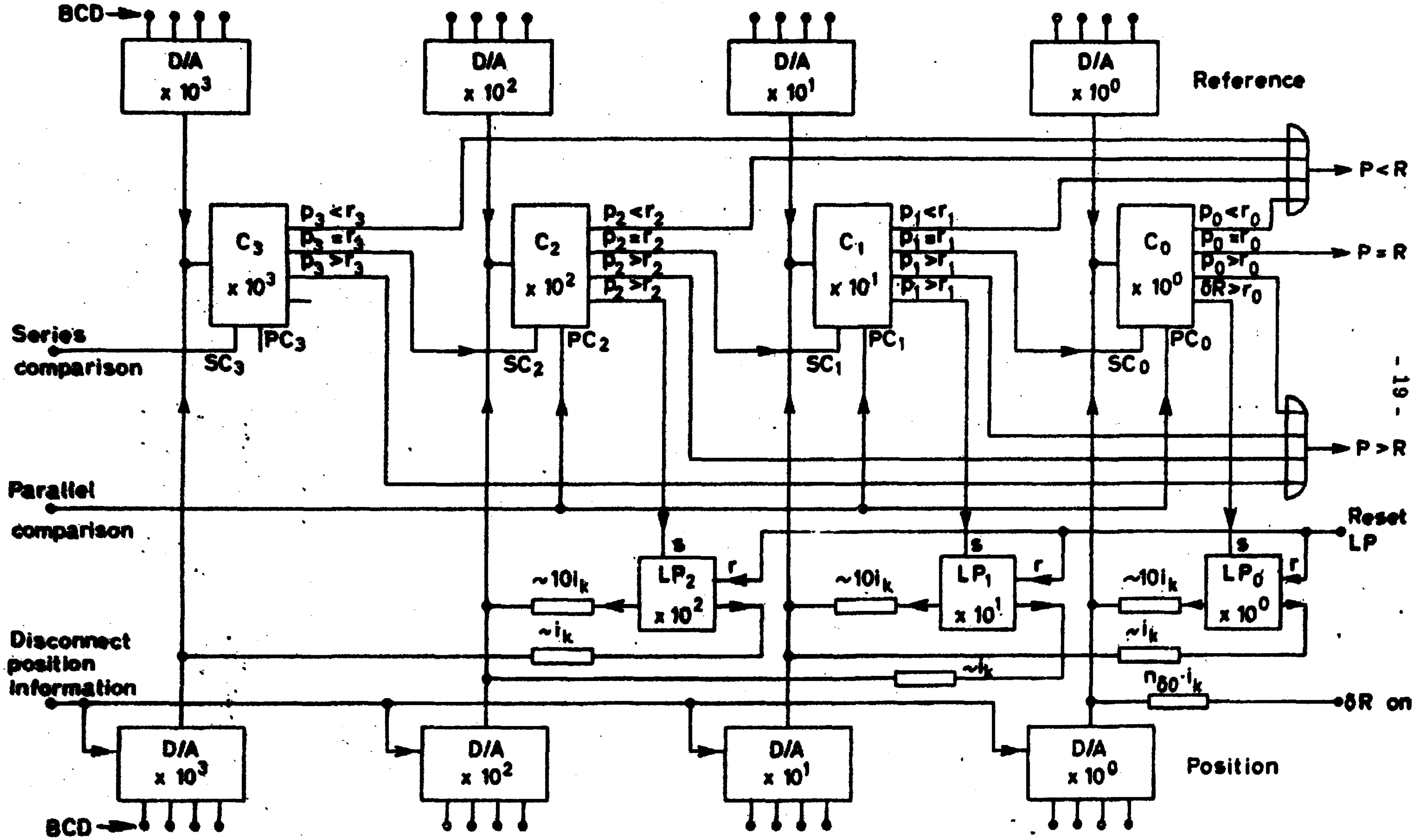
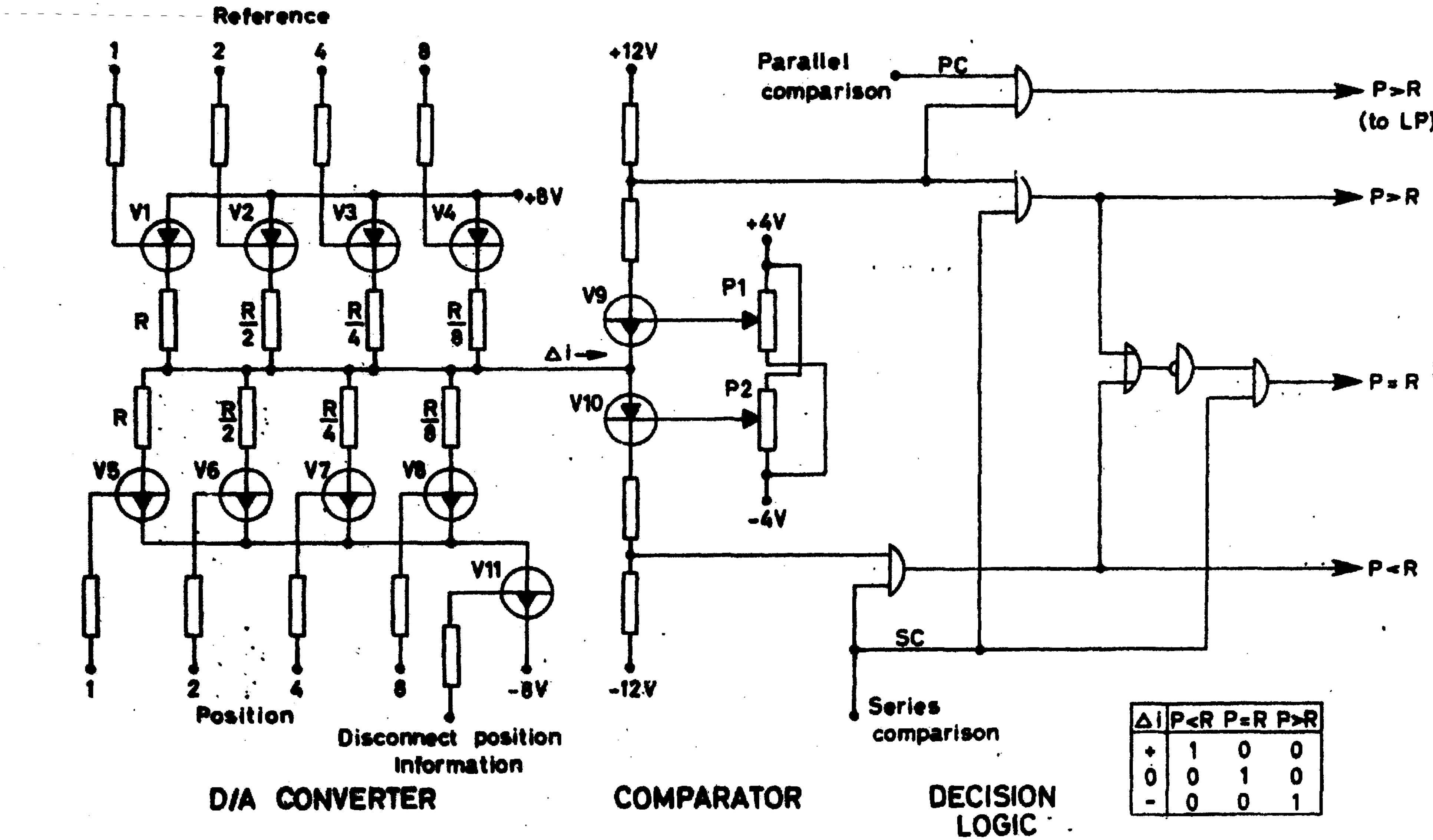


Fig. 7. SUBTRACTOR



Δi	P<R	P=R	P>R
+	1	0	0
0	0	1	0
-	0	0	1

Fig. 8

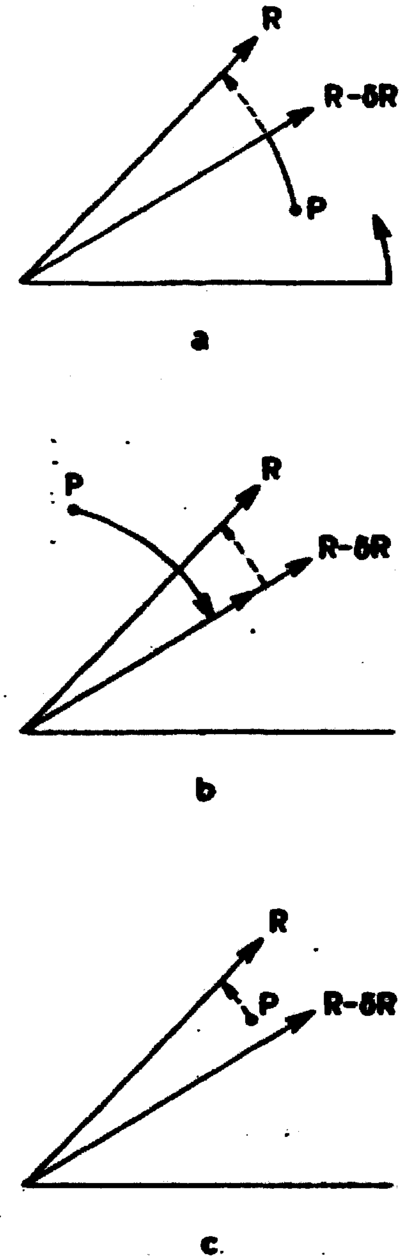


Fig. 9. CHARACTERISTIC PATTERNS OF SLEWING AND INCHING MODE

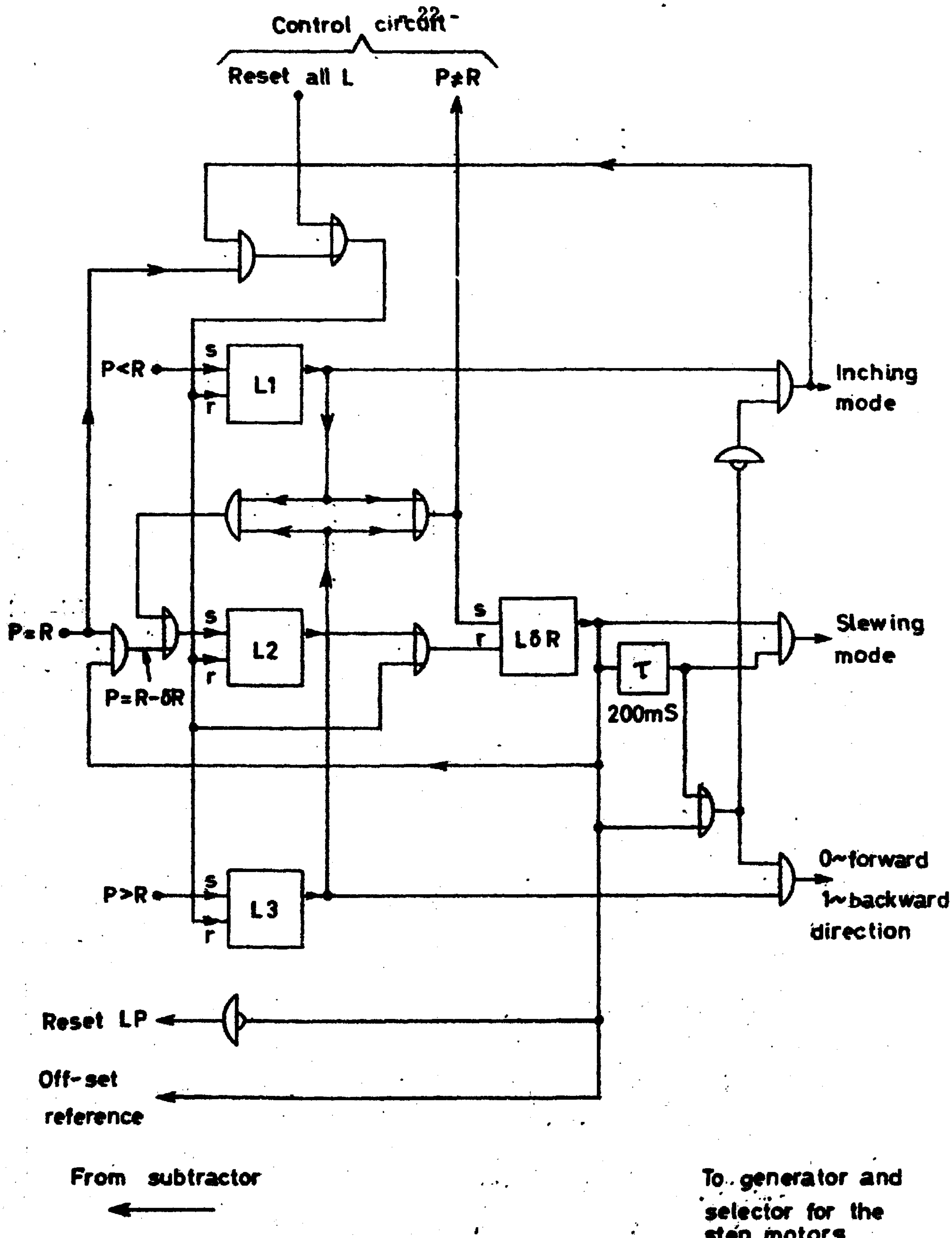


Fig. 10. ERROR VALUE LOGIC

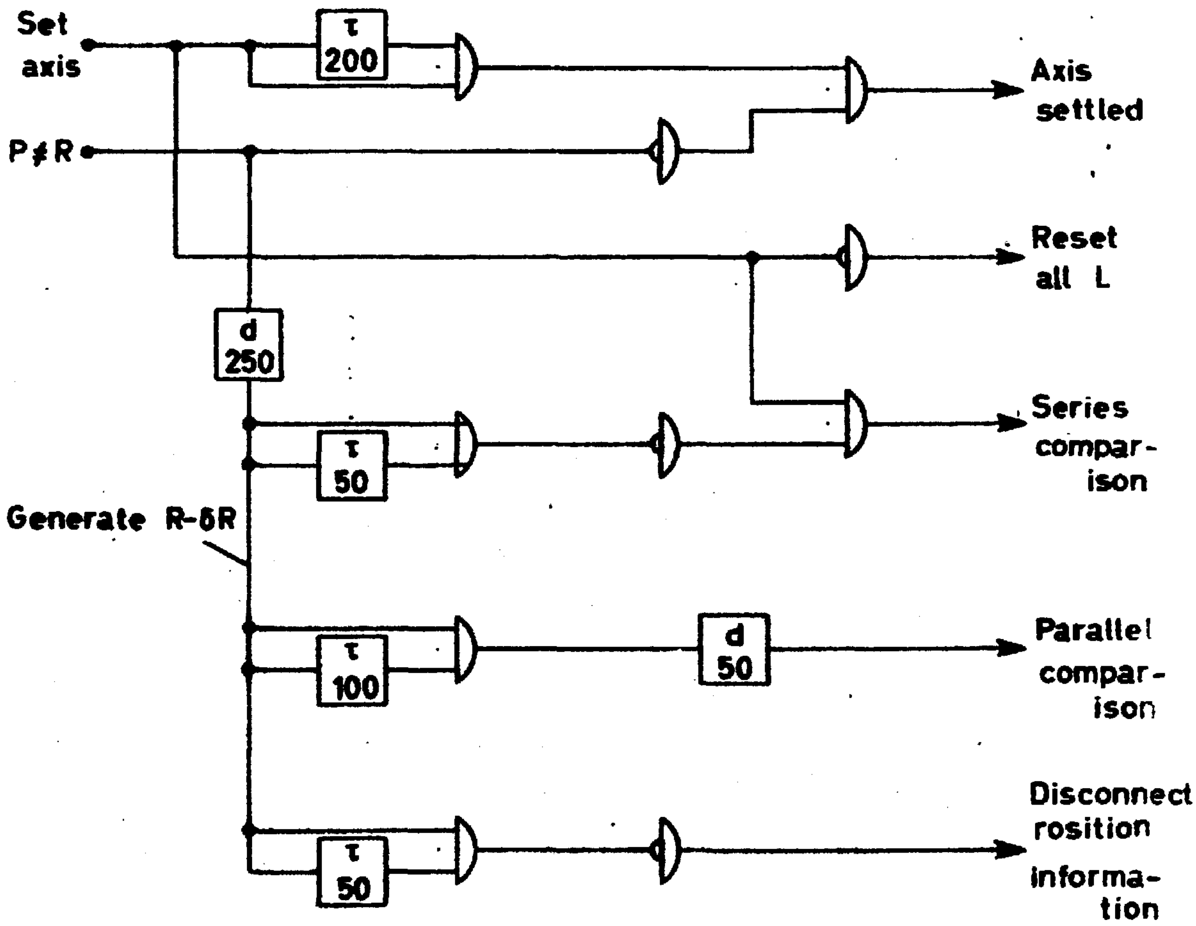


Fig. 11. CONTROL CIRCUIT

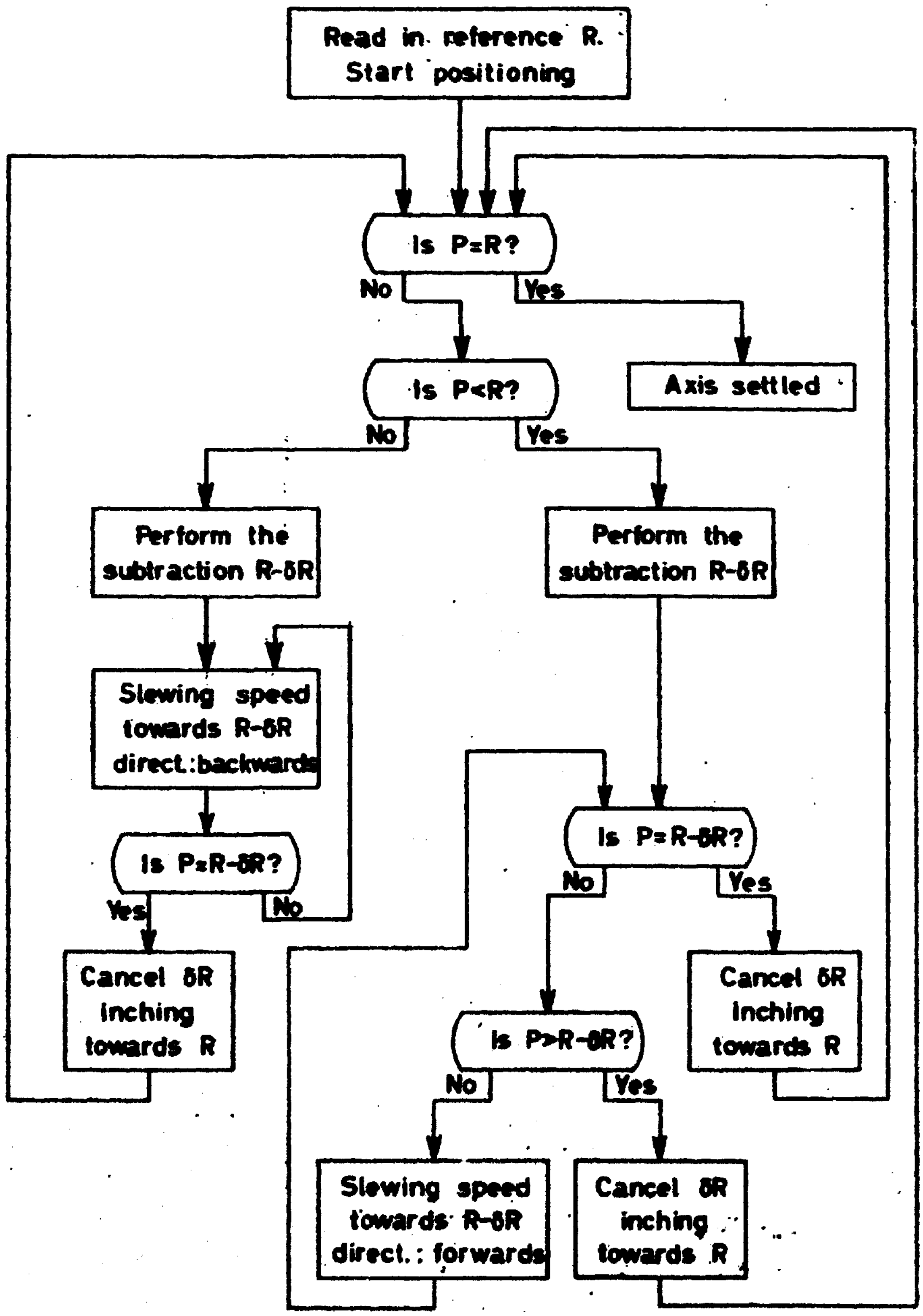


Fig. 12. FLOWCHART OF THE POSITIONING SYSTEM

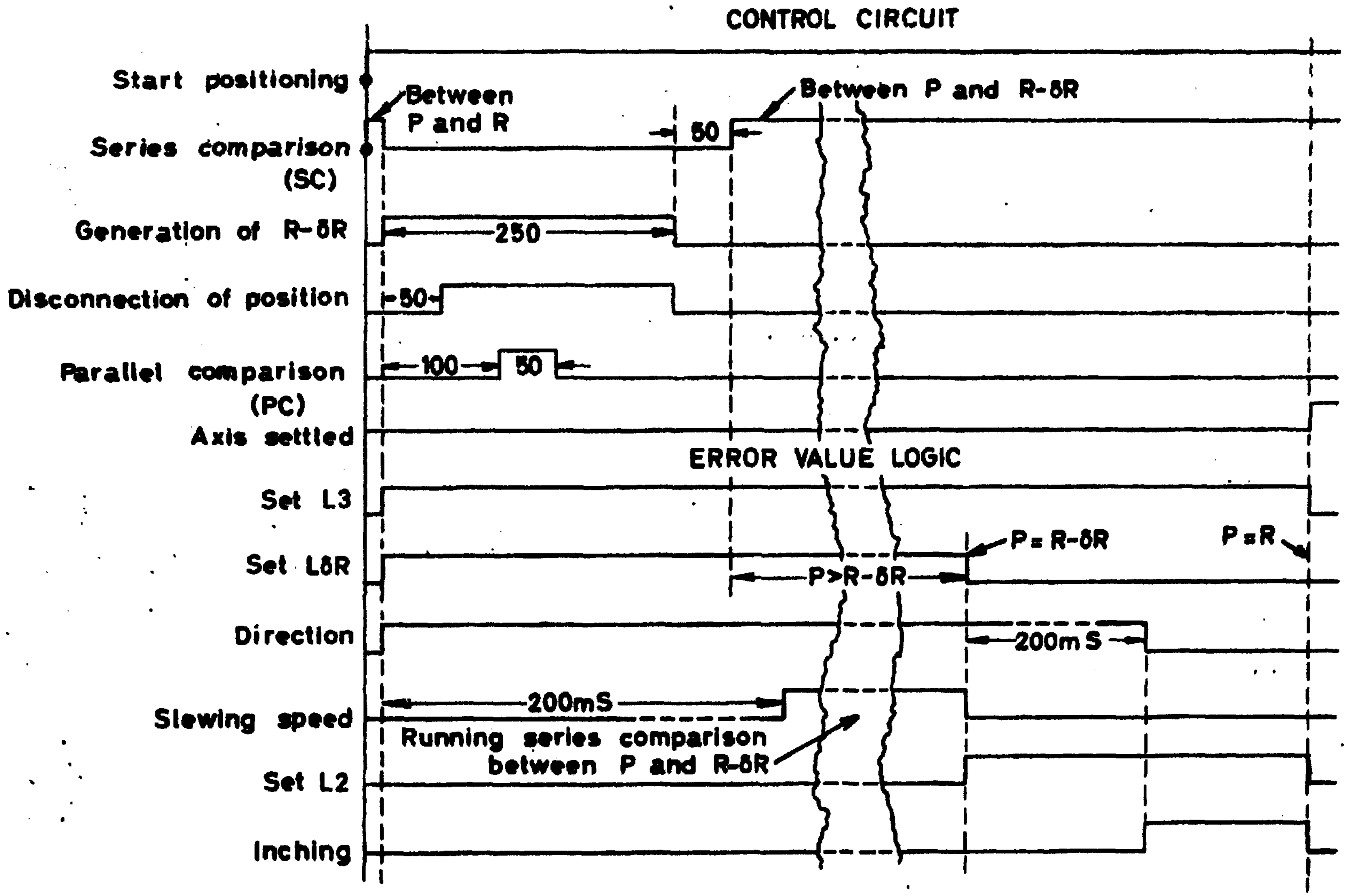


Fig.13. TIME CHART OF ONE AXIS SETTING CYCLE. STARTING CONDITIONS P>R

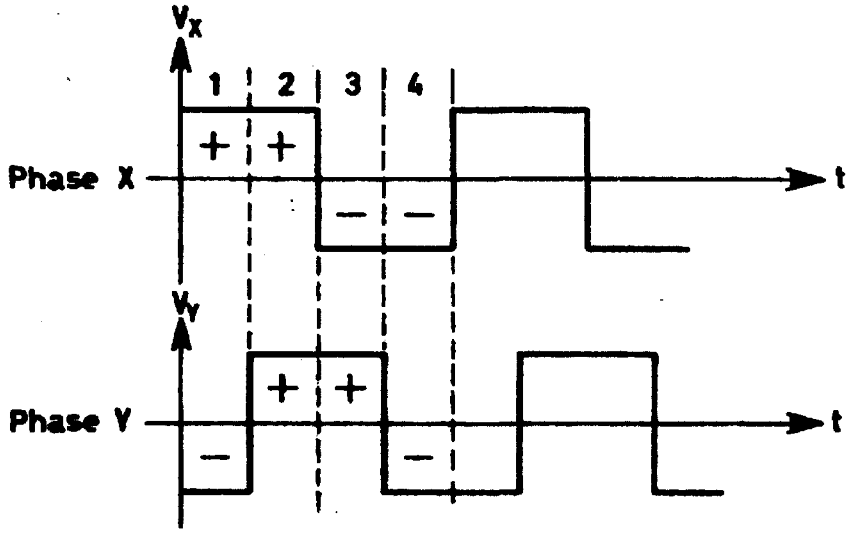


Fig. 14. VOLTAGE PATTERN OF
COMMUTATED DC STEPPING MOTOR

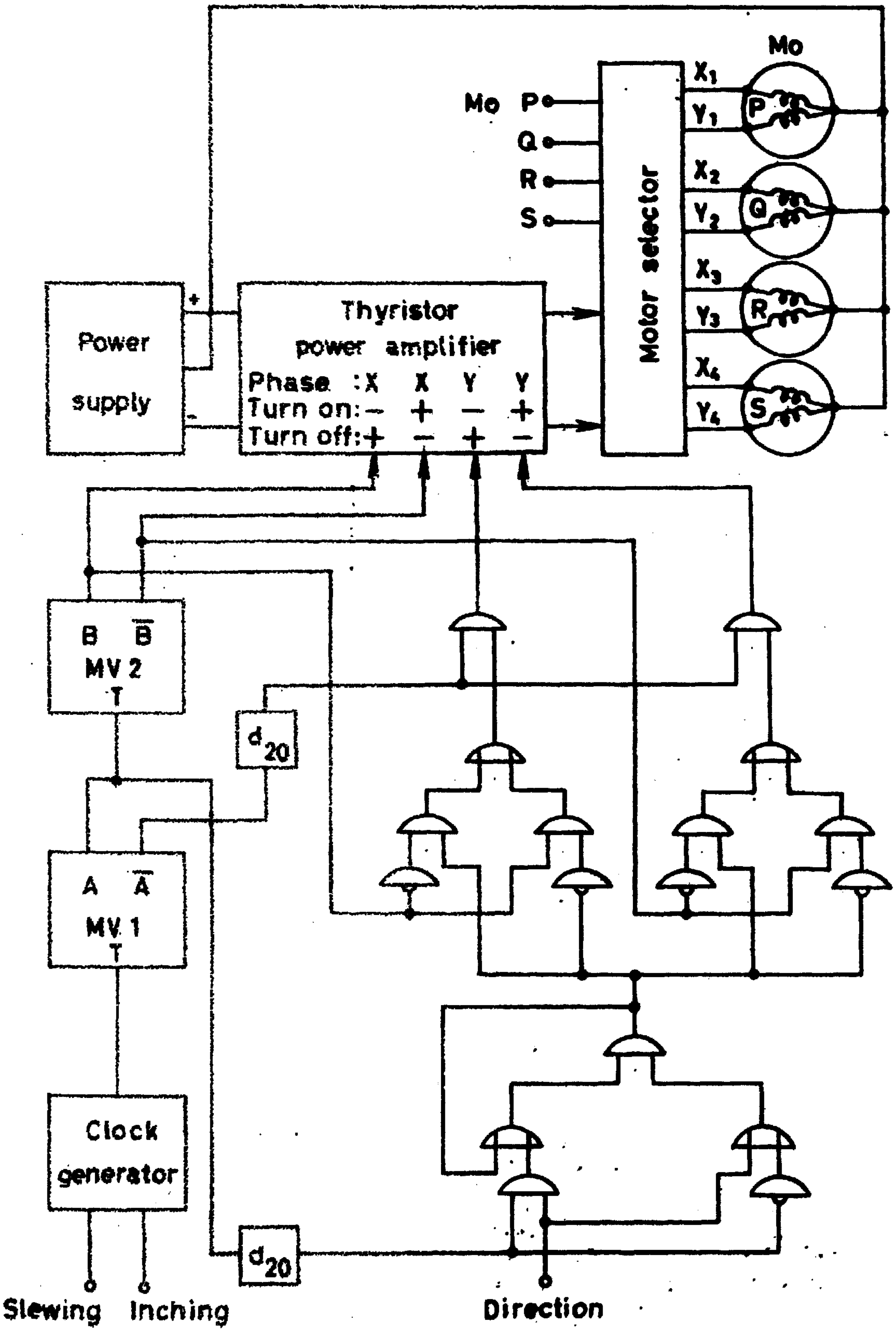


Fig. 15. PATTERN GENERATOR AND SELECTOR OF THE STEP MOTORS

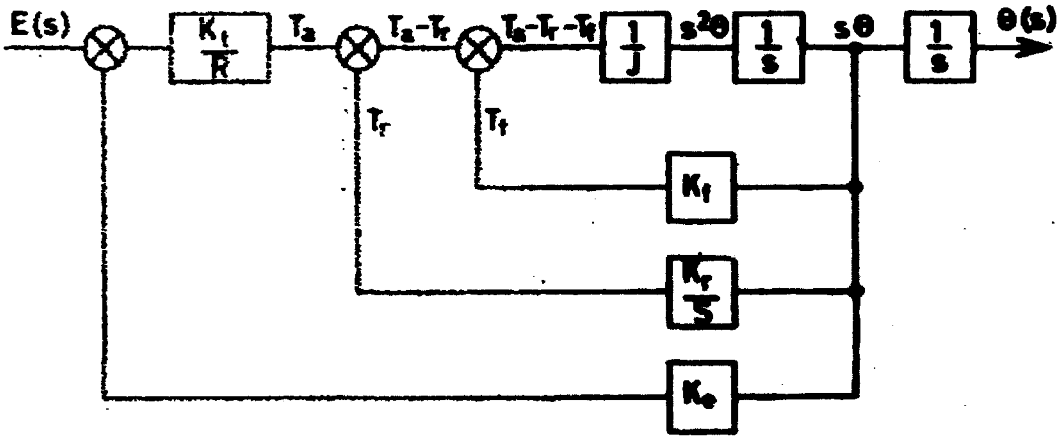


Fig.16. BLOCK DIAGRAM OF THE STEP MOTOR